

REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEMIANNUAL STATUS REPORT #5

1N-11112

C/S GW 167534
jmx

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF
MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED
CONDITIONS FOR PLANETARY ATMOSPHERES

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February 1, 1986 through July 31, 1986

Submitted by

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(NASA-CR-177267) LABORATORY EVALUATION AND
APPLICATION OF MICROWAVE ABSORPTION
PROPERTIES UNDER SIMULATED CONDITIONS FOR
PLANETARY ATMOSPHERES Semiannual Status
Report, 1 Feb. - 31 Jul. 1986 (Georgia Inst. G3/91

N86-28040

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TABLE OF CONTENTS

	<u>PAGE</u>
I. INTRODUCTION AND SUMMARY.....	1
II. THE GEORGIA TECH RADIO ASTRONOMY AND PROPAGATION (R.A.P.) FACILITY.....	5
III. RESULTS OF LABORATORY MEASUREMENTS AND THEIR APPLICATION.....	9
IV. PUBLICATIONS AND INTERACTIONS WITH OTHER INVESTIGATORS.....	10
V. CONCLUSION.....	12
VI. REFERENCES.....	13
VII. KEY FIGURES.....	14
VIII. APPENDICES.....	18

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often lead to significant misinterpretation of available opacity data. Steffes and Eshleman (1981) showed that under environmental conditions corresponding to the middle atmosphere of Venus, the microwave absorption due to atmospheric SO_2 was 50 percent greater than that calculated from Van Vleck-Weiskopff theory. Similarly, results obtained for the microwave opacity from gaseous H_2SO_4 under simulated Venus conditions, during the first two years of Grant NAGW-533 (February 1, 1984 through January 31, 1986), showed that not only was the opacity from H_2SO_4 much greater than theoretically predicted, but that its frequency (wavelength) dependence was far different than that theoretically predicted (Steffes, 1985 and Steffes, 1986a). The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by radio occultation experiments, and over a range of frequencies which correspond to both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements.

In the first two years of Grant NAGW-533 (i.e., February 1, 1984 through January 31, 1986), this facility was developed, and then operated, in order to evaluate the microwave absorbing properties of gaseous sulfuric acid (H_2SO_4) under Venus atmospheric conditions. The initial results, obtained at 13.4 cm and 3.6 cm wavelengths, were applied to measurements from Mariner 5, Mariner 10, and Pioneer-Venus Radio Occultation experiments, to determine abundances of gaseous sulfuric acid in the Venus atmosphere, with accuracies exceeding those achieved with in-situ instruments (Steffes, 1985). Measurements of the microwave properties of the vapors accompanying liquid H_2SO_4 also resulted in more accurate estimates of the vapor pressure behavior of sulfuric acid, which are critical for modeling the behavior and structure of the Venus atmosphere. Later efforts concentrated on making laboratory measurements of the microwave absorption from gaseous H_2SO_4 at wavelengths from 1.2 to 22 cm under simulated Venus conditions. Additional measurements of the vapor pressure behavior of sulfuric acid were also made. We applied these results to radio astronomical observations of Venus which have been made in the same wavelength range, in order to better model the structure of H_2SO_4 and SO_2 abundance in the Venus atmosphere, and to resolve temporal variations of their abundances on a planet-wide basis. The results of this effort have been especially rewarding in that the unique frequency and pressure dependences measured for the absorption from gaseous H_2SO_4 in these wavelength ranges has finally explained what were thought to be inconsistencies between measurements of the absorption in the Venus atmosphere at 13.3 and 3.6 cm wavelengths and those obtained in the 1 to 3 cm wavelength range. We describe these effects, and the resulting limitations they place on abundances of gaseous H_2SO_4 and SO_2 in the Venus atmosphere, in a paper entitled, "Evaluation of the Microwave Spectrum of

Venus in the 1.2 to 22 Centimeter Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," which was submitted in February and has been accepted for publication in The Astrophysical Journal (v. 310, November 1, 1986).

Additional activities during the first half of the current grant year (February 1, 1986 through July 31, 1986) involving application of the laboratory measurements of simulated Venus atmospheres have included assistance to the Magellan program office (J.P.L.) in characterizing effects of the atmosphere on planned microwave radar and radiometric experiments originally planned to characterize surface and geologic parameters. The laboratory measurements have also suggested that a substantial dip in the Venus microwave emission, related to the abundance of gaseous sulfuric acid, should exist near the 2.25 cm wavelength. Since no observations of the Venus emission at this wavelength have ever been published, we hope to use the 140-foot NRAO telescope to not only confirm the presence of the predicted dip, but to use such a dip to determine a planet-wide average for sulfuric acid vapor abundance below the main cloud layer.

The highest priority activity for this grant year has been laboratory measurements of the microwave properties of the simulated atmospheres of the outer planets and their satellites. As described in the most recent Annual Status Report for Grant NAGW-533 (February 1, 1985 through January 31, 1986), our planetary atmospheres simulator underwent a major redesign late last year to permit measurements of the microwave properties of simulated Jovian atmospheres. Further developmental work has been necessary in order to minimize the safety risks involved with high pressure simulations using hydrogen gas at very low temperatures, as required for the outer planets. A

more complete description of this work is given in Section II of this report. However, since many of the low temperature, high pressure tests were initially conducted using the nonexplosive gas nitrogen (N_2), which is the primary constituent of the atmosphere of the Saturnian satellite Titan, useful data for microwave refractivity and absorptivity of nitrogen atmospheres under simulated Titan conditions has been obtained at frequencies from 2.2 GHz to 21.7 GHz (1.3 cm to 13.7 cm). Such data is useful in interpretation of both Voyager 1 radio occultation measurements of the Titan atmosphere, as well as radio astronomical observations of Titan.

During the second half of the current grant year (August 1, 1986 through January 31, 1987), we hope to be able to complete measurements of the microwave absorptivity and refractivity of both hydrogen/helium (H_2/He) atmospheres and of gaseous ammonia (NH_3) in an H_2/He atmosphere under simulated conditions for the outer planets at frequencies from 1.3 GHz to 27 GHz (wavelengths from 1.1 cm to 22 cm). These laboratory results will directly apply to measurements of atmospheric microwave opacity at Jupiter, Saturn, and Uranus made by the Voyager spacecraft, as well as to radio astronomical observations of the outer planets and to radio science experiments from future missions to the outer planets.

Beyond the current grant year, our goals are to continue such laboratory measurements of the microwave absorption and refraction from other potential microwave absorbers contained in the outer planets' atmospheres, including methane (CH_4) and phosphine (PH_3). We likewise would hope to be able to pursue a program of analysis and application of these results to microwave data for the outer planets such as Voyager Radio Occultation experiments and earth-based radio astronomical observations.

Of equal importance, we feel, would be the further analysis and application of our laboratory results for the microwave absorption from gaseous H_2SO_4 in the Venus atmosphere. Our long term goal would be a detailed analysis of available multi-spectral microwave opacity data from Venus including data from the Pioneer-Venus Radio Occultation experiments and earth-based radio and radar astronomical observations, such as the kinds which have been performed at the NRAO Very Large Array (VLA) and at stations in the Deep Space Network (DSN). The new measurements of Venus microwave emission at 2.25 cm and 1.9 cm made with the NRAO 140-foot telescope will be an especially important contribution to this data set. This would provide a chance to determine both spatial and temporal variations in the abundances of both H_2SO_4 and SO_2 in the Venus atmosphere.

II. THE GEORGIA TECH RADIO ASTRONOMY AND PROPAGATION (R.A.P.) FACILITY

The basic configuration of the planetary atmospheres simulator developed at Georgia Tech for use in measurement of the microwave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in the first two Annual Status Report(s) for Grant NAGW-533 (February 1, 1984 through January 31, 1985 and February 1, 1985 through January 31, 1986). It is also discussed at length in Steffes (1985 and 1986b). The updated simulator system, shown in Figure 1, is currently configured for simulations of the outer planets. Measurements of the microwave opacity and refractivity of test gas mixtures can be performed at frequencies from 1.3 GHz to 27 GHz (wavelengths from 1.2 cm to 22 cm). While the pressure chamber itself is capable of containing pressures up to 10 atmospheres, and the temperature chamber is capable of achieving temperatures as low as 150 K, it has been

found that the combination of high pressures and low temperatures can create a substantial problem with sealing the pressure chamber. In previous simulations, small leakages from the pressure vessel presented little or no danger to the experimenters. The use of gaseous hydrogen (H_2) in the outer planets simulations has required the development of new procedures and equipment for conducting such simulations. Such precautions include the addition of a hydrogen leakage sensor which is placed inside the temperature chamber immediately outside the pressure vessel (see Figure 1). This sensor can detect the potentially dangerous build-up of hydrogen gas within the freezer unit. A ventilation pump has also been provided which, if needed, can be used to draw any escaping hydrogen gas out of the freezer compartment. Additional precautions have included the construction of ramps which allow all of the equipment to be moved out-of-doors to a concrete slab immediately adjacent to the laboratory. All experiments which employ gaseous hydrogen can thus be conducted out-of-doors in order to avoid any build-up of hydrogen gas within the laboratory. A covered outdoor storage area for hydrogen and helium gases has also been constructed in order to allow safe storage of these gases, and to expedite the out-of-doors experiments. It is noteworthy that funding for the hydrogen leakage sensor, for construction of the outdoor gas storage and experimental areas, and for special tools required for sealing the pressure vessel (over \$2,000) has been provided by the Georgia Institute of Technology, in support of planetary atmospheres research at Georgia Tech. In addition, two vacuum sensors have been added to the system. These sensors not only allow accurate determination of pressure vessel evacuation, but they can also be used for accurately determining the abundance of test gases, which are typically very small at low temperatures, due to low saturation vapor pressures.

Initial testing of the new simulator configuration for the outer planets was conducted using nitrogen (N_2) gas both because of its relative safety as compared with hydrogen, and because measurements of both the refractivity and absorptivity of nitrogen under simulated conditions for the Saturnian satellite Titan were considered important for interpreting results of the Voyager 1 radio occultation studies of the Titan atmosphere (Lindal et al., 1983 and 1985).

The first tests of the system showed that the pressure vessel could easily hold pressures of 7 atmospheres at room temperature with minimal leakage. However, when the system was cooled to 150 K, significant leakage occurred. A quick review of pressure vessel construction can shed some light on this problem: The pressure vessel is essentially a 13-inch diameter stainless steel cylinder (0.375-inch wall thickness) with a 0.375-inch thickness stainless steel plate welded to the bottom of the cylinder. At the top of the cylinder is a 0.5-inch thick cylindrical flange which is welded to the cylinder. The top plate (0.5-inch thickness stainless steel) bolts to the flange using 16 stainless steel bolts, along with a pressure sealant O-ring, and sealant putty which is placed outside the O-ring. (See Figure 2.) All electrical connections are made via hermetically sealed feed-through connectors mounted on the top plate.

Two causes for the increased leakage rate at extremely low temperatures have been found. The first was simply due to metal contraction. When the pressure vessel was cooled to 150 K, it was found that most of the fastener bolts had loosened due to contraction of the stainless steel. Thus, removal of the cooled pressure vessel from the freezer was necessary so that the bolts could be tightened while it was still very cold, and it was then immediately

replaced inside the freezer. The special lifting frame and pulley system which was designed for easily moving the pressure vessel in and out of the freezer has been especially useful for this task. However, even after retightening of the fastener bolts on the cold pressure vessel, substantial leakage still occurred.

The cause of the continued leakage was found to be the sealing materials used in the pressure vessel. As shown in Figure 2, the seal used when placing the top plate on the pressure vessel consists of a 0.385-inch cross-section O-ring accompanied by a ring of putty-type sealing material. As was the case in the recent Space Shuttle accident, seals which normally function well at room temperature can malfunction when placed under extremely cold conditions. This is due to increasing brittleness of the O-ring and putty seals, accompanied by a higher probability of cracks developing due to the brittleness. Initially, as suggested by several seal material vendors, we used an O-ring made from vulcanized rubber and RTV-silicone putty. The relatively poor performance of this seal caused us to experiment with several other types of sealing materials. We found that nearly all materials typically used in such seals became brittle at 150 K. However, we found that O-rings fabricated from the material Viton were less likely to develop cracks at this temperature. It was also found that RTV-silicone became extremely brittle at 150 K, and was very susceptible to cracking. As a result, we now use a more fibrous silicone composite material for the sealing putty.

The overall result has been a pressure vessel capable of maintaining 6 atmospheres of pressure at a temperature of 170 K, with an acceptably small leak ratio. While the resulting range of pressures and temperatures which can be tested are not quite as large as originally hoped, they do represent the

pressure-temperature ranges over which most of the microwave opacity in the Jupiter atmosphere has been observed, and thus will be very useful in interpretation of microwave opacity data from Voyager I and II radio occultation experiments, as well as from earth based radio astronomical observations, and opacity measurements to be made using the Galileo probe.

III. RESULTS OF LABORATORY MEASUREMENTS AND THEIR APPLICATION

Measurements made of the microwave refraction and absorption from Nitrogen (N_2) under simulated conditions for Titan are shown in Table I. While no absorption was measured at any frequency from 2.2 GHz to 21.7 GHz, upper limits for the opacity from N_2 can be set. This is especially important since N_2 may very well be the source of the 3.6 cm (8.4 GHz) opacity detected by Voyager I radio occultation studies of the Titan atmosphere (Lindal et al., 1985). Also shown in Table I is the refractivity, N , and the refractivity normalized by molecule number density. Since the normalized refractivity is used directly to determine atmospheric pressure from measurements of the atmospheric refractivity at a given altitude, an accurate expression for normalized refractivity at the temperature of that altitude.

When inverting the Voyager I refractivity data obtained at 2.3 GHz at Titan, in order to develop a temperature-pressure profile for Titan's atmosphere, Lindal et al. (1983) assumed an exponential atmosphere with surface temperature 94 K, and a constant value for the density normalized refractivity of gaseous N_2 (1.093 ± 0.0004 N-units/molecule/cm³). This value for normalized refractivity was obtained by Essen and Froome (1951) based on a single measurement of the refractivity of nitrogen under standard laboratory conditions at a single frequency (24 GHz). This value is included, for

comparison, in Table I. We have measured the refractivity of nitrogen over a wide range of temperatures (down to 156 K) and over a wide range of frequencies (2.2 GHz to 21.7 GHz) in order to determine whether any temperature or frequency variations of the density-normalized refractivity existed, and to estimate their effects on the interpretation of the refractivity data. It appears that the refractivity of N_2 , at a frequency of 2.2 GHz and at a temperature of 156 K, is slightly lower than the value reported at standard temperature and pressure at a frequency of 24 GHz by Essen and Froome (1951). However, the difference is at the limit of resolution of the present experiment, so that the statistical significance is difficult to determine. These results suggest that the surface atmospheric pressure at Titan may be as much as 10% greater than the 1496 ± 20 mbar pressure given by Lindal et al. (1983).

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

At the beginning of the current grant year, a paper was completed and accepted for publication in The Astrophysical Journal, describing results and applications of experiments performed during the second year of Grant NAGW-533 (Steffes, 1986a). This paper is described at length in Section I of this report. In May 1985, a paper was presented at the Conference on Jovian Atmospheres, at the Goddard Institute for Space Studies (New York) entitled, "Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Simulated Conditions for the Outer Planets." This paper described our plans and capabilities for simulating outer planets atmospheres and measuring microwave properties of those atmospheres. At the beginning of this year, a revised manuscript was completed and submitted for inclusion in a NASA Conference Proceedings for this conference (Steffes, 1986b). More

informal contacts have been maintained with groups at the California Institute of Technology (Dr. Duane O. Muhleman), at the Stanford Center for Radar Astronomy (V. Eshleman, director), and at JPL (Drs. Michael J. Klein, Michael Janssen, A. J. Kliore, and Samuel Gulkis). We have also had discussions with members of the Magellan Program Office at JPL with regards to using results from our laboratory measurements of simulated Venus atmospheres in planning mission experiments.

Another source of close interaction with other planetary atmospheres principal investigators has been Dr. Steffes' membership in the Planetary Atmospheres Management and Operations Working Group (PAMOWG). Travel support for attendance at PAMOWG meetings has been provided by Georgia Tech. Travel to Paris, France in November is also being planned so as to allow presentation of our research results from this current grant year at both the 18th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society and at an accompanying meeting, entitled "Laboratory Measurements for Planetary Science." Support for this travel from the Georgia Tech Foundation, Inc. has been solicited.

Additional publications which describe our research activities in the Planetary Atmospheres to the public have also been released. The first, entitled "Probing Venus," was a two-page color article describing the results of our work simulating the microwave properties of the Venus atmosphere, and appeared in the publication Research Horizons, published by the Georgia Institute of Technology (Winter 1986, Volume 3, Number 4, pp. 8-9). It is attached as Appendix 1. As Appendix 2, we have attached an article which appeared in the Tuesday, June 10 edition of The Atlanta Constitution (pg. 34a) and in the Tuesday, June 10 edition of The Atlanta Journal (pg. 22a), entitled

"Tech Making Down-to-Earth Studies of Outer Space." This article likewise appeals to a large public audience. As Appendix 3, we have attached a short article, entitled "Remote Sensing Reveals Much About Planets," which appeared in the Georgia Tech Whistle (Volume 12, Number 18, May 26, 1986), a newspaper for Georgia Tech employees.

V. CONCLUSION

During the first half of the current grant year (February 1, 1986 through July 31, 1986), we have completed construction of the outer planets simulator and conducted measurements of the microwave absorption and refraction from nitrogen (N_2) under simulated Titan conditions. We have also applied the results of these and previous laboratory measurements to a wide range of microwave opacity measurements, in order to derive constituent densities and distributions in planetary atmospheres such as Venus. In the second half of this grant year, we hope to measure microwave absorption from ammonia (NH_3) in a hydrogen/helium atmosphere (H_2/He) under simulated Jovian conditions. We will likewise continue work on the application of our newly derived absorptivity spectra to a wide range of spacecraft and radio astronomical data.

MICROWAVE
RADIATION ABSORPTION
ATMOSPHERIC REFRACTION
OPACITY DENSITY
RADIO OCCULTATION

PLANETARY ATMOSPHERES
NITROGEN
TITAN
VENUS
RADIO WAVES
SPACE ENVIRONMENT SIMULATION
RADIO ASTRONOMY

VI. REFERENCES

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Steffes, P. G. (1985). Laboratory measurements of the microwave opacity and vapor pressure of sulfuric acid under simulated conditions for the middle atmosphere of Venus. Icarus 64, 576-585.

Steffes, P. G. (1986a). Evaluation of the microwave spectrum of Venus in the 1.2 to 22 centimeter wavelength range based on laboratory measurements of constituent gas opacities. Astrophysical Journal 310, November 1, 1986. In press.

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VII. KEY FIGURES

TABLE I
LABORATORY MEASUREMENTS OF NITROGEN (N₂) REFRACTIVITY AND ABSORPTIVITY

Frequency, GHz	Conditions	Refractivity $N = 10^6 (n-1)$	Refractivity Normalized by Number Density ³ (N-units/molecule/cm ³)	Absorptivity (dB/km)	Source
2.255	T = 295 ± 1 K P = 5 ± .2 atm	1354 ± 70	(1.0886 ± .104) × 10 ⁻¹⁷	< .14	This work
2.255	T = 188 K ± 10 K P = 5.5 ± .2 atm	2156 ± 120	(.9979 ± .145) × 10 ⁻¹⁷	< .05	This work
2.255	T = 156 K ± 12 K P = 5 K	2509 ± 130	(.9422 ± .154) - .112	< .1	This work
9.28	T = 273 K P = 1 atm	293.4 ± 1.4	(1.0912 ± .005) × 10 ⁻¹⁷	-----	Birnbaum, Kryder and Lyons (1951)
13.3	T = 295 ± 1 K P = 6 ± .2 atm	1475 ± 75	(.988 ± .086) × 10 ⁻¹⁷	< 9	This work
21.7	T = 295 ± 1 K P = 5.7 ± .2 atm	1447.0 ± 75	(1.059 ± .096) × 10 ⁻¹⁷	< 4.5	This work
24.0	T = 273 K P = 1 atm	294.1 ± 0.1	(1.0938 ± .0004) × 10 ⁻¹⁷	-----	Essen and Froome (1951)

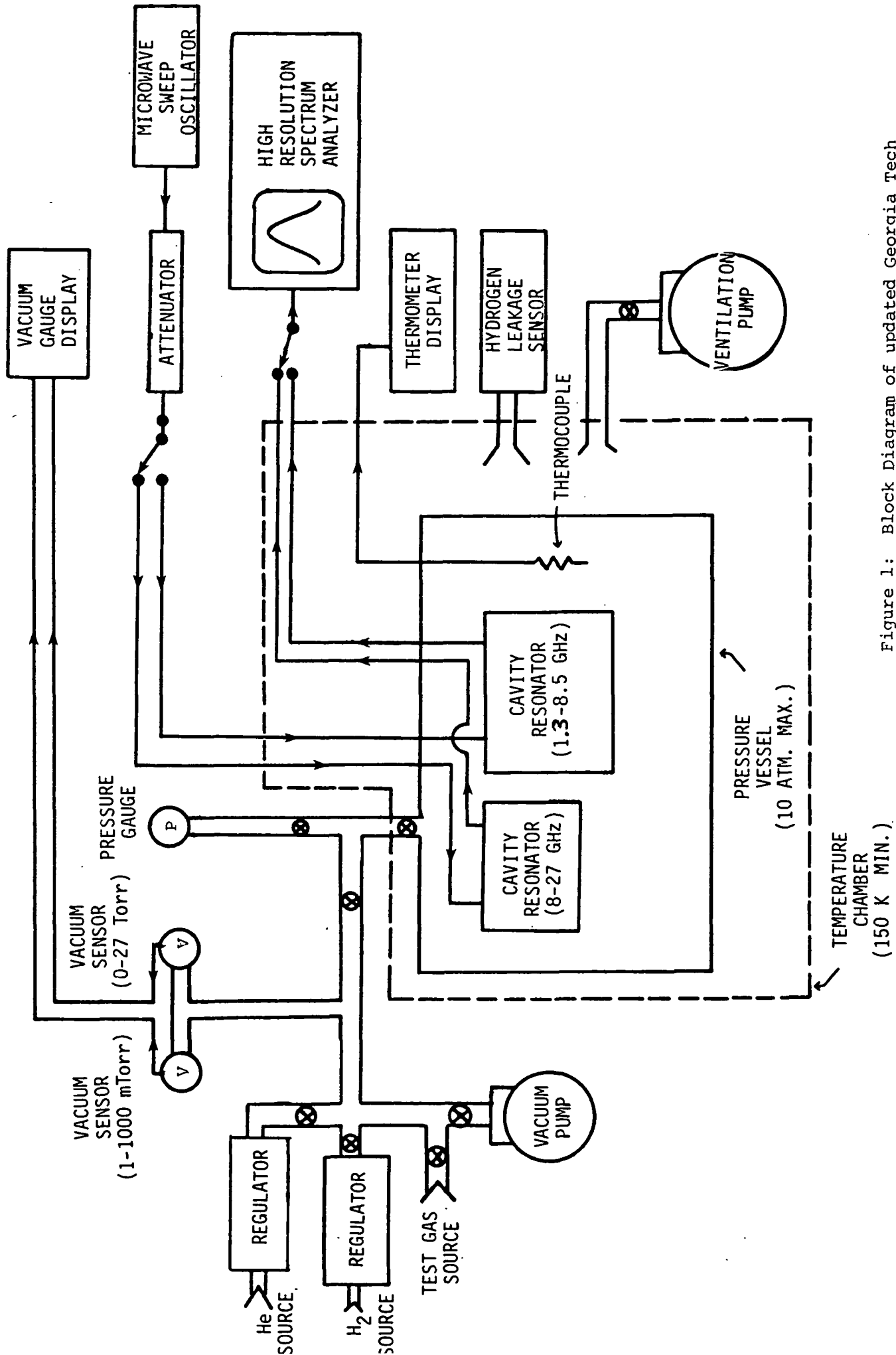


Figure 1: Block Diagram of updated Georgia Tech Planetary Atmospheres Simulator, as Configured for measurements of microwave properties of gases under simulated conditions for the outer planets.

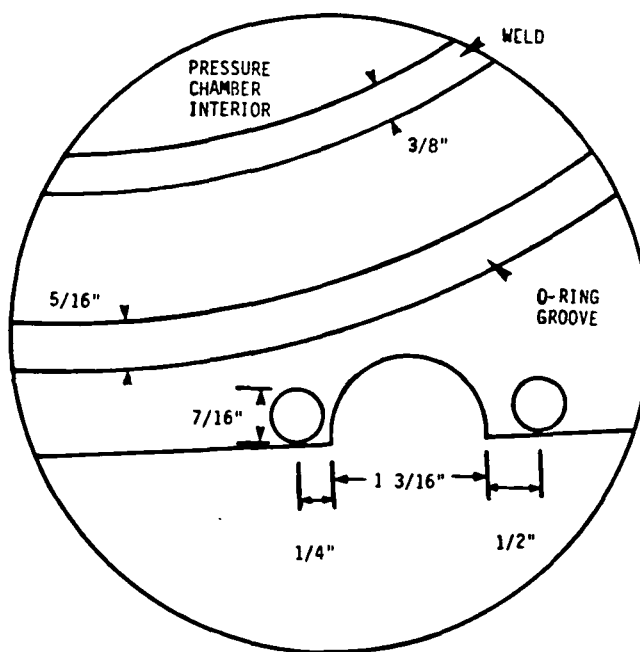
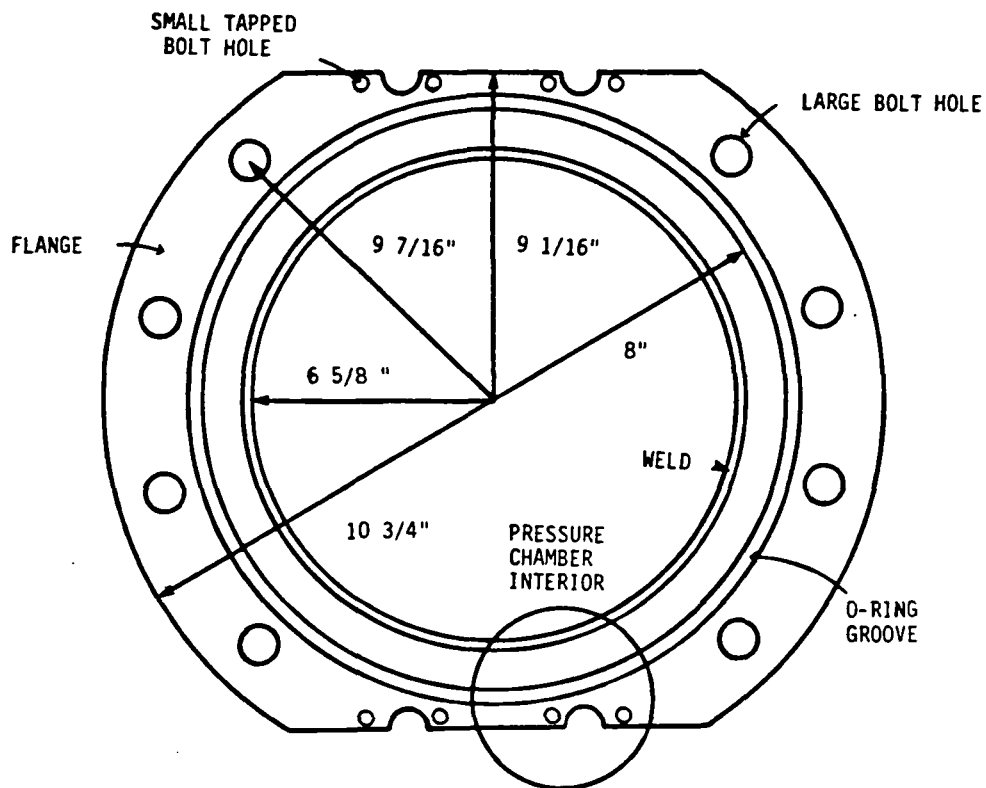


Figure 2: Sketch of pressure vessel, as viewed from above, with the top plate removed. Note the welded flange, with groove for the O-ring.